Noise Control for Buildings and Manufacturing Plants

Hoover & Keith Inc.
11391 Meadowglen, Suite D
Houston, TX 77082
(281) 496-9876

Lecture Notes for. . .

NOISE CONTROL FOR BUILDINGS, MANUFACTURING PLANTS, EQUIPMENT AND PRODUCTS

LECTURERS:

REGINALD H. KEITH

AND

ASHTON TAYLOR

Noise Control Courses given annually since 1969

HOOVER & KEITH INC.
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Houston, TX 77082
(281) 496-9876

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CONTENTS

Acknowledgement

			Page
	INTRODUCTION TO ACOUSTICS		
	1-1.	Introduction	1-1
	1-2.	Decibels	1-1
	1-3.	Sound power level	1-2
	1-4.	Sound intensity level	1-3
	1-5.	Sound pressure level	1-3
	1-6.	Frequency	1-4
	1-7.	Speed of sound and wavelength	1-6
	1-8.	Temporal variations	1-8
	1-9.	Loudness	1-8
	1-10.	Decibel Manipulation	1-9
		References	1-13
		Problems	1-13
	NOISE CRITERIA		
	2-1.	Noise criteria for speech communication	2-1
	2-2.	Indoor noise criteria	2-2
	2-3.	Outdoor noise criteria	2-6
		Reference	2-13
		Problems	2-14
3.	VIBRATION CRITERIA		
	3-1.	Vibration in buildings	3-1
	3-2.	Vibration criteria	3-1
	3-3.	Vibration isolation	3-4
	3-4.	Conversion Charts	3-7
		Problems	3-9
4.	INDOOR SOUND DISTRIBUTION - ROOM ACOUSTICS		
	4-1.	Analogy between light and sound	4-1
	4-2.	Sound in a room	4-1
	4-3.	Room Constant by calculation	4-2
	4-4.	Room Constant estimate	4-5
	4-5.	SPL distribution in a room	4-7
	4-6.	Qualifications	4-10
	4-7.	Sound absorption materials and techniques	4-13
	4-8.	Reverberation time	4-14
		References	4-14
		Problems	4-15
5.	SOUND TRANSMISSION LOSS		
	5-1.	Introduction	5-1
	5-2.	Transmission loss of walls, doors, and windows	5-3
	5-3.	Transmission loss of floor-ceiling combinations	5-18
	5-4.	Data Forms 5 and 6	5-27
		References	5-27
		Problems	5-27
6.	OUTDOOR SOUND PROPAGATION RECEPTION		
	6-1.	Distance effects	6-1
	6-2.	Atmospheric effects	6-5
	6-3.	Terrain and vegetation effects	6-8
	6-4.	Reception of outdoor noise indoors	
	6-5.	Sound reflection from walls and buildings	6-11
	6-6.	Outdoor background noise of rain and wind in the trees	6-14
	6-7.	Radiation of indoor noise to the out-of-doors	
	6-8.	Acoustic center of a group of outdoor sources	6-22
		References	6-23
		Problems	6-24
7.	SOUND LEVEL DATA FOR ELECTRICAL AND MECHANICAL HVAC EQUIPMENT		
	7-1.	Data collection and study	
	7-2.	Sound pressure and sound power level data	7-1
	7-3.	Equipment noise summaries	7-2
	7-4.	Packaged chillers with reciprocating compressors	7-2
	7-5.	Packaged chillers with rotary-screw compressors	7-3
	7-6.	Packaged chillers with centrifugal compressors	7-3
	7-7.	Built-up refrigeration machines	7-4
	7-8.	Absorption machines	7-5
	7-9.	Boilers	7-5
	7-10.	Steam valves	7-5
	7-11.	Cooling towers and evaporative condensers	7-6
	7-12.	Pumps	7-10

		Page
7-13.	Fans	7-12
7-14.	Air compressors	-7-12
7-15.	Reciprocating engines	7-12
7-16.	Gas turbine engines	7-15
7-17.	Electric motors	7-17
7-18.	Steam turbines	7-18
7-19.	Gears	7-18
7-20.	Generators	7-19
7-21.	Transformers	7-19
7-22.	Multiple sources	7-21
7-23.	Noise specifications	7-21
	References	7-22
8.	**SOUND LEVEL DATA FOR TRANSPORTATION, CONSTRUCTION, MANUFACTURING, AND POWER PLANT EQUIPMENT**	
8-1.	Transportation equipment noise	8-1
8-2.	Construction equipment noise	8-3
8-3.	Noise in manufacturing plants	8-7
8-4.	Power plant equipment noise	8-13
8-5.	Conclusion	8-18
8-6.	References	8-18
9.	**THE DUCTED VENTILATION SYSTEM**	
9-1.	Nature of the noise control requirements	9-1
9-2.	Noise sources	9-2
9-3.	Noise attenuating elements in a duct system	9-9
9-4.	Calculation procedure	9-15
9-5.	Rooftop units	9-19
9-6.	Expansion chambers or plenums	9-21
9-7.	Protective facings for sound absorptive materials	9-22
9-8.	Calculation example	9-23
	References	9-23
10.	**AIRBORNE SOUND CONTROL**	
10-1.	Basic steps in noise control	10-1
10-2.	Noise control approaches	10-3
10-3.	Noise control strategies	10-7
10-4.	Airborne sound control treatments	10-8
10-5.	Outdoor barriers	10-8
10-6.	Indoor barriers	10-12
10-7.	Partial enclosures	10-13
10-8.	Complete enclosures	10-15
10-9.	Pipe wrapping, lagging	10-16
10-10.	Radiating area	10-17
10-11.	Impact noise	10-18
10-12.	Air jet noise	10-19
10-13.	Mufflers	10-20

		Page
10-14.	Personnel booths	10-21
	References	10-22
11	**VIBRATION CONTROLS**	
11-1.	Vibration damping	11-1
11-2.	Vibration isolation in machine design	11-3
11-3.	Types of vibration isolators	11-4
11-4.	Vibration isolation of HVAC equipment	1-6
11-5.	Vibration data for reciprocating engine installations	1-26
11-6.	Vibration isolation of stationary reciprocating engines	11-27
11-7.	Vibration isolation of turbine engines	11-29
	References	11-30
12.	**CASE HISTORIES OF NOISE CONTROL IN MANUFACTURING PLANTS**	
12-1.	Example 1. Partial enclosure	12-2
12-2.	Example 2. Partial enclosure	12-3
12-3.	Example 3. Complete enclosure	12-4
12-4.	Example 4. Vibration damping	12-6
12-5.	Example 5. Duct wrapping and damping	12-6
12-6.	Example 6. Enclosure and pipe wrapping	12-7
12-7.	Example 7. Air exhaust muffling	12-8
12-8.	Example 8. Air exhaust noise of pneumatic tool	12-8
12-9.	Example 9. Fan mufflers	12-9
12-10.	Example 10. Absorption inside an enclosure	12-10
12-11.	Example 11. Room absorption	12-11
12-12.	Example 12. Room absorption and personnel booths	12-11
12-13.	Example 13. Divider wall	12-13
12-14.	Example 14. Product quieting	12-13
12-15.	Example 15. Product quieting	12-16
12-16.	Example 16. Quieter design	12-17
12-17.	Example 17. Quieter design	12-18
	References	12-21
13.	**NOISE CONTROL PROGRAM FOR OSHA COMPLIANCE**	
13-1.	Hearing conservation criteria	
13-2.	OSHA noise control program for general industry	13-3
13-3.	An effective hearing conservation program (HCP)	13-7

			Page
	13-4	Considerations for the total program	13-9
	13-5	Noise measurements	13-11
	13-6	Preparation of OSHA compliance plan	13-11
	13-7.	The noise control work	13-12
	13-8.	Presentation of results	13-12
		References	13-15
14.	SOUND AND VIBRATION MEASUREMENTS AND INSTRUMENTATION		
	14-1.	Measurements and instrumentation for OSHA applications	14-
	14-2.	Measurement of noise and vibration in buildings	14-8
	14-3.	Community noise measurements	14-8
	14-4.	Conclusion	14-9
15.	NOISE CONTROL COSTS		
	15-1.	Noise monitoring and audiometric testing	15-
	15-2.	Noise control products and materials	15-
	15-3.	Cost of total noise control program	15-3
	15-4.	Other costs	15-5
		References	15-5
16.	BIBLIOGRAPHY AND SOURCES OF INFORMATION ON NOISE CONTROL		
	16-1.	Books and manuals	16-1
	16-2.	Periodicals and journals	16-2
	16-3.	Meetings on noise control	16-2
17.	DATA FORMS		
	17-1.	Quality of analysis procedure	17-1
	17-2.	Instructions for Data Form 1	17-2
	17-3.	Instructions for Data Form 2	17-3
	17-4.	Instructions for Data Form 3	17-3
	17-5.	Instructions for Data Form 4	17-4
	17-6.	Instructions for Data Form 5	17-4
	17-7.	Instructions for Data Form 6	17-5
		Data Forms	17-6

Chapter 1

Introduction To Acoustics

1-1. INTRODUCTION

This opening chapter presents some basic quantities and definitions used to describe sound and its properties. Detailed mathematical derivations are not given in this manual; they may be found in suitable textbooks or references, some of which are listed in Chapter 16.

English units are used throughout this manual for conventional dimensions, such as length, volume, speed and weight. Metric units are used in special applications for expressing certain acoustical reference quantities, such as 20 micropascal, the reference base for sound pressure level. Many of these acoustical reference quantities have been standardized by the International Standards Organization (ISO) and are used extensively in U.S. standards and guidelines published by the American National Standards Institute (ANSI). Conversion tables for metric equivalents are given at the end of this chapter.

For the purposes of the material contained in this manual perceptible acoustical sensations can be generally classified into two broad categories, these are:

Sound - A disturbance in an elastic medium such as a gas, a liquid, or a solid, that is capable of being detected by the human ear. Noise is then defined as "unwanted sound," or "sound without value."

Vibration - A periodic motion, or displacement in a solid elastic medium.

Although this differentiation is useful in presenting acoustical concepts, in reality sound and vibration are often interrelated. That is, sound is often the result of acoustical energy radiation from vibrating structures, and sound can induce structures to vibrate.

Three important characteristics of sound and vibration control are as follows:

Magnitude or Level - This is a measure of the intensity of the acoustical energy. The unit of level is the decibel, abbreviated dB.

Frequency or Pitch - Frequency is a measure of the number of times per second that a cyclic, or periodic disturbance repeats. The unit of frequency is Hertz, abbreviated as Hz. One Hertz is one cycle per second.

Time Pattern - This may relate to the operation of a sound source with respect to time, or may be a measure of the exposure as function of time of any listener to a sound or noise.

In this chapter Sections 1-2 through 1-5 describe the application of the decibel to the measurement of sound power, intensity, and pressure. Section 1-6 and 1-7 include material on frequency, wavelength, and speed of sound. In Sections 1-8 and 1-9 temporal factors and methods of rating the loudness of sound are discussed. In Section 1-10 arithmetical methods for combining, adding, and subtracting decibels are described.

1-2. DECIBELS

The basic unit of level in acoustics is the "decibel" (abbreviated dB). In acoustics, the term "level" is used to designate that the quantity is referred to some reference value, which is either stated or implied. The decibel (dB), as used in acoustics, is a unit expressing the ratio of two quantities that are proportional to power. The decibel level is equal to 10 times the common logarithm of a power ratio; or

$$dB = 10\log_{10}\left(\frac{W_2}{W_1}\right) \quad (1\text{-}1)$$

In this equation W_2 is the magnitude of the power under evaluation and W_1 is the magnitude of reference power. If the power W_1 is an accepted standard reference, the decibel level is standardized to that reference. In acoustics, the decibel is used to quantify sound pressure levels that people hear, sound power levels radiated by sound sources, the sound power loss through a wall, and in other uses, such as simply "a noise reduction of 15 dB" (a reduction relative to the original sound level condition). Decibels are always related to logarithms to the base 10, so the subscript of 10 is usually omitted. It is important to realize that the decibel is in reality a dimensionless quantity (somewhat analogous to "percent"). Therefore, when determining the decibel level, reference needs to be made to both the quantity under evaluation and the reference level. It is also instructive to note that with the fixed reference level, the decibel level of the source under evaluation is determined solely by the magnitude of the power. Thus, if the magnitude of two different powers differ by a factor of 100 then the decibel levels differ by 20 dB.

1-3. SOUND POWER LEVELS (L_W or PWL)

Sound power level is a measure of the quantity of acoustical energy radiated by a sound source. This sound power then produces a sound pressure at some distance that a listener may hear. How the sound power is radiated and distributed determines the sound pressure level at a specific location. It will be seen in Chapter 4 that the sound pressure level for an indoor sound source is influenced by the room containing the source; for example, sound pressure levels may vary as much as 5 to 15 dB at distances of 5 to 10 feet from the source because of the acoustic characteristics of the room. Therefore, errors in determining the room characteristics or in ignoring them altogether are important either in evaluating sound pressure level data or in the design of new spaces. On the other hand, sound power level, when correctly determined, is an indication of the sound radiated by the source and is independent of the room containing the source. Chapters 4 and 7 procedures will show that sound power level data can be used to compare sound data submittals more accurately than by the use of sound pressure data, and to estimate sound pressure levels for a variety of rooms. Thus, there is technical need for the generally higher quality sound power level data.

[redacted]s

[redacted] (1-2)

Where W is the sound power of a sound source in watts, and W_{ref} is the reference power in watts. Unless otherwise stated the power, W, is the effective root mean square (rms) sound power. The reference power (W_{ref}) is 10^{-12} watts. Before the US joined the ISO in acoustics terminology, the reference power in this country was 10^{-13} watts, so it is important in using old data (earlier than about 1963) to ascertain the power level base that was used. If the sound power level value is expressed in dB relative to 10^{-13} W, it can be converted to dB relative to 10^{-12} W by subtracting 10 dB from the value. Special care must be used to not confuse decibels of sound pressure with decibels of sound power. It is often recommended that power level values always be followed by the notation "dB re 10^{-12} W." The abbreviation PWL is often used to represent sound power level, and the notation L_W is normally used in equations involving power level. This custom is followed in the manual.

There are two notable limitations regarding sound power level data. First, sound powdr data cannot be measured directly but are calculated from sound pressure level data. The procedures involve either comparative sound pressure level measurements between a so-called standard sound source and the source under test (i.e. the "substitution method"), or very careful acoustic qualifications of the test room in which the sound pressure levels of the source are measured. Either of these procedures can be involved and requires quality equipment and knowledgeable personnel. However, when the measurements are carried out properly, the resulting sound power level data generally are more reliable than most ordinary sound pressure level data.

Secondly, the directivity characteristics of a source are not necessarily determined when the sound power level data are obtained. Technically, the measurement of sound power level takes into account the fact that different amounts of sound radiate in different directions from the source, but when the measurements are made in a reverberant or semireverberant room, the actual directionality pattern of the radiated sound is not obtained. If directivity data are desired, measurements must be made either outdoors, or in a totally anechoic test room where reflected sound cannot distort the sound radiation pattern, or in some instances by using sound intensity measurement techniques. These comments apply equally well to both sound pressure and sound power measurements.

1-4. SOUND INTENSITY LEVEL (L_I)

For a source that radiates uniformly in all directions, normally referred to as a point source, its sound power in watts spreads out over a spherical, or hemispherical area. As the distance from the source increases, the area through which the power is transmitted increases. Thus, the power per unit area decreases. This power per unit area is termed the sound intensity. It is this sound intensity that directly relates sound power to sound pressure. Strictly speaking, sound intensity is the average flow of sound energy through a unit area in a sound field. Sound intensity is also a vector quantity, that is, it has both a magnitude and direction. The sound intensity level (in decibels) is defined by:

$$L_I = 10\log\left(\frac{I}{I_{ref}}\right) \qquad (1\text{-}3)$$

Where I is the observed sound intensity (watts/sq. meter) produced by a source and I_{ref} (watts/sq. meter) is the reference intensity. Unless otherwise stated the intensity, I, is the effective root mean square (rms) sound intensity. The intensity reference level (I_{ref}) is 10^{-12}W/m^2 (watts/square meter).

The conversion between sound intensity level (in dB) and sound power level (in dB) is as follows:

$$L_w = 10\log\left[A\left(\frac{I}{I_{ref}}\right)\right] \qquad (1\text{-}4)$$

where A is the cross-sectional area over which the average intensity is determined in square meters (m^2). Note this can also be written as:

$$L_w = 10\log\left(\frac{I}{I_{ref}}\right) + 10\log(A) \qquad (1\text{-}5)$$

If A is in English units, then equation 1-5 can be written as:

$$L_w = 10\log\left(\frac{I}{I_{ref}}\right) + 10\log(A) - 10.3 \qquad (1\text{-}6)$$

Note, that if the area, A, completely closes the sound source, these equations can provide the total sound power level of the source. However, care must be taken to ensure that the intensity used is representative of the total area. This can be done by using an area weighted intensity or by logarithmically combining individual L_W's.

Like sound power, sound intensity is not directly measurable, but sound intensity can be obtained from sound pressure measurements. Under free field conditions where the energy flow direction is predictable (outdoors for example) the magnitude of the sound pressure level is equivalent to the magnitude of the intensity level. This results because, under these conditions, the intensity (I) is directly proportional to the square of the sound pressure (p^2). This is the key to the relationship between sound pressure level and sound power level. This is also the reason that when two sounds combine, the resulting sound level is proportional to the log of the sum of the squared pressures (i.e. the sum of the p^2's) not the sum of the pressures (i.e. not the sum of the p's). That is, when two sounds combine, it is the intensities that add not the pressures.

Recent advances in measurement and computational techniques have resulted in equipment that determine sound intensity immediately, both magnitude and direction. Using this instrumentation, sound intensity measurements can be conducted in complicated environments where the relationship between intensity and pressure is not as direct as they are in a free field environment.

The abbreviation L_I is used to represent sound intensity level. The use of IL as an abbreviation is not recommended since this may be confused with the same abbreviation for "Insertion Loss."

1-5. SOUND PRESSURE LEVEL (L_p or SPL)

Sound waves produce small oscillations of pressure just above and below atmospheric pressure. These pressure oscillations impinge on the ear drum and create the sensation of sound. A sound level meter, with its microphone, is also sensitive to sound pressure.

[redacted] by:

[redacted] $\left(\frac{\quad}{p_{ref}}\right)^2$ (1-7)

Where p is the observed sound pressure and p_{ref} is the reference pressure. Unless otherwise stated the pressure, p, is the effective root mean square (rms) sound pressure. This equation may also be written as:

$$L_p = 20\log\left(\frac{p}{p_{ref}}\right) \qquad (1\text{-}8)$$

Although both formulas are correct, it is instructive to consider sound pressure level as the log of the pressure squared (formula 1-7). This is because, as discussed in Section 1-4, when combining sound pressure levels, in almost all cases, it is the square of the pressure ratios (i.e. $[p/p_{ref}]^2$'s) that should be summed not the pressure ratios (i.e. not the $[p/p_{ref}]$'s). This is also true for sound pressure level subtraction and averaging.

The reference pressure (p_{ref}) is 20 micropascal or 20 μPa (1 Pascal, a unit of pressure, equals 1 Newton/m^2). In the earlier system of units, this same reference pressure was expressed as 2×10^{-10} bar, or $.0002 \times 10^{-4}$ microbar, where one bar is standard atmospheric pressure. This reference pressure represents approximately the faintest sound that can be heard by a young, healthy human ear when the sound occurs in the frequency region of maximum hearing sensitivity, about 1000 Hertz (Hz). A 20-μPa pressure is 0 dB on the sound pressure level scale. In the strictest sense, a sound pressure level should be stated completely, including the reference pressure base, such as "85 decibels relative to 20 μPa." However, in normal practice and in this manual, the reference sound pressure is omitted but it is nevertheless implied.

The abbreviation SPL is often used to represent sound pressure level, and the notation L_p is normally [redacted]s, both in this manual and in the general acoustics literature. Sound pressure levels are used to evaluate the effects of sound by comparison with appropriate sound pressure level criteria. While sound pressure level data taken under one set of conditions are used to predict sound pressure levels under other installation conditions this prediction process implicitly involves sound power level calculations.

1-6. FREQUENCY

Frequency is analogous to "pitch." The normal frequency range of hearing for most people extends from a low frequency of about 20 to 50 Hz (a "rumbling" sound) up to a high frequency of about 10,000 to 15,000 Hz (a "hissy" sound) or even higher for some people. Frequency characteristics are important for at least the following four reasons: (1) People have different hearing sensitivity to different frequencies of sound (generally, people hear better in the upper frequency region of about 500-5000 Hz and are therefore most annoyed by loud sounds in this frequency region); (2) Mid- and high-frequency sounds of high intensity and long duration are prime contributors to hearing loss; (3) Different types of electrical and mechanical equipment produce different amounts of low-, middle-, and high-frequency noise; and (4) Noise control materials and treatments vary in their effectiveness as a function of frequency (usually, low frequency noise is more difficult to control; most treatments perform best at mid and high frequencies).

A. UNIT OF FREQUENCY, HERTZ

When a piano string vibrates 440 times per second, its frequency is 440 vibrations per second or 440 Hz. Before the US joined the ISO in standardization of many technical terms (about 1963), this unit was known as "cycles per second."

B. DISCRETE FREQUENCIES OR TONAL COMPONENTS

When an electrical or mechanical device operates at a constant speed and has some repetitive mechanism that produces an intense sound, that sound may be concentrated at a frequency related to a shaft rotation of the device and the number of blades, teeth, or piston firings per rotation. Examples are: the blade passage frequency of a fan or propeller, the gear-tooth contact frequency of a gear or timing belt, the high pitch tones of a motor associated with rotor bars, or cooling fan blades, the firing rate of an internal combustion engine, the impeller blade frequency of a pump or compressor, and the hum of a transformer. These frequencies are designated "discrete frequencies" or "tones" and the frequency is usually calculable with knowledge of shaft speed and/or the source components.

The principal frequency is known as the "fundamental," and most such sounds also contain many "harmonics" of the fundamental. The harmonics are multiples of the fundamental frequency, i.e., 2, 3, 4, 5, etc. times the fundamental. For example, in a gear train, where gear tooth contacts occur at the rate of 200 per second, the fundamental frequency would be 200 Hz, and it is very probable that the gear would also generate sounds at 400, 600, 800, 1000, 1200 Hz and so on for possibly 10 to 15 harmonics. Considerable sound energy is often concentrated at these discrete frequencies, and the sounds are more noticeable and sometimes more annoying because of their presence. Discrete frequencies can be located and identified within a general background of broadband noise

(noise that has all frequencies present, such as the roar of a jet aircraft or the water noise in a cooling tower or waterfall) with the use of narrowband filters that can be swept through the full frequency range of interest.

C. OCTAVE BANDS OF FREQUENCY

Typically, a piece of mechanical equipment, such as a diesel engine, a fan, or a cooling tower, generates and radiates some noise over the entire audible range of hearing. The amount and frequency distribution of the total noise is determined by measurement with a frequency analyzer. One common type is an octave band analyzer, which has a set of contiguous filters covering essentially the full frequency range of human hearing. Each filter has a bandwidth of one octave, and nine such filters cover the range of interest for most noise problems. The standard octave frequencies are given in Table 1-1. An octave represents a bandwidth covering a frequency interval with the higher frequency limit being twice the lower. The first column of Table 1-1 lists the bandwidth frequencies and the second column gives the geometric mean frequencies of the bands. The latter values are the frequencies that are used to label the various octave bands. For example, the 1000-Hz octave band contains all the noise falling between 707 Hz ($1000 \div \sqrt{2}$) and 1414 Hz ($1000 \times \sqrt{2}$). The frequency characteristics of these filters have been standardized by agreement (ANSI S1.11 and ANSI S1.6) [1,2]*. In some instances reference is made to "low," "mid," and "high" frequency sound. This distinction is somewhat arbitrary, but for the purposes of this manual, low frequency sound includes the 31 through 125 Hz octave bands, mid frequency sound includes the 250 through 1,000 Hz octave bands, and high frequency sound includes the 2,000 through 8,000 Hz octave bands.

For finer resolution of data, narrower bandwidth filters are sometimes used; for example, finer constant percentage bandwidth filters (e.g. half-octave, third-octave, and tenth-octave filters), and constant width filters (e.g. 1 Hz, 10 Hz, etc.). The spectral information presented in this manual is in terms of full octave bands. This has been found to be a sufficient resolution for many engineering considerations. Laboratory test data is often obtained and presented in terms of 1/3 octave bands. A reasonably approximate conversion from 1/3 to full octave bands can be made (see **D.** below). In certain cases the octave band is referred to as a "full octave" or "1/1 octave" to differentiate it from partial octaves such as the 1/3 or 1/2 octave bands. The term "overall" is used to designate the total noise without any filtering.

Table 1-1. Bandwidth and geometric mean frequency of standard octave frequency bands used in analysis procedures.

Octave Frequency Range, Hz	Geometric Mean Frequency of Band, Hz
22-44	31
44-88	63
88-175	125
175-350	250
350-700	500
700-1400	1000
1400-2800	2000
2800-5600	4000
5600-11200	8000

Numbers in brackets indicate references that are listed at the end of the chapter in which they are used.

D. BAND LEVELS

The band level, in dB, is dependent on the frequency width of the band and how the acoustic energy is distributed within the band. For broadband acoustical signals (i.e. signals without dominant pure tones and with equal energy distributed throughout the band) the level of the sound or vibration for a bandwidth is dependent on the frequency width of the filter. For these signals an approximate conversion can be made between different bandwidths by:

$$\text{SPL}_{\text{Band 2}} \ \text{dB} = 10\log\left(\frac{BW_2}{BW_1}\right) \qquad (1\text{-}9)$$

Where BW_2 is the bandwidth of the new band, BW_1 is the bandwidth of the original band. For example, if the level is given as 85 dB for a bandwidth of 100 Hz, then the level for a bandwidth of 10 Hz is determined as follows:

$$\begin{aligned} 85 + 10\log(10/100) &= 85 + 10\log(0.1) \\ &= 85 + (-10) \\ &= 85 - 10 \\ &= 75 \text{ dB} \end{aligned}$$

The corresponding level for a bandwidth of 1.0 Hz would be 65 dB. For broadband sounds the conversion from full octave to 1/3 octave is -4.8 dB (since a 1/3 octave band is .333 the bandwidth of a full octave band).

E. A-, B-, and C-WEIGHTED SOUND LEVELS

Sound level meters usually have "weighting networks" that are designed to represent the frequency characteristics of the average human ear for various sound intensities. The frequency characteristics of the A-, B-, and C-weighting networks are shown in Figure 1-1 along with the resulting frequency weighting of the octave band filters that is normally assumed when measuring broadband sound. The relative frequency response of the average ear approximates the A curve when sound pressure levels of about 20 to 30 dB are heard. For such quiet sounds, the ear has fairly poor sensitivity in the low-frequency region. The B curve represents approximately the frequency response of hearing sensitivity for sounds having 60- to 70-dB sound pressure level, and the C curve shows the almost flat frequency response of the ear for loud sounds in the range of about 90 to 100 dB. Annoyance usually occurs when an unwanted noise intrudes into an otherwise generally low sound level environment. At such times, the ear is listening with a sensitivity resembling the A curve. Thus, judgment tests are often carried out to compare the loudness, noisiness, annoyance, or intrusiveness of a sound or noise to the A-weighted sound level of that sound. The correlation is generally quite good. when comparing a family of sources with similar spectrum shapes, such as several dishwashers, but not for comparing the sound level of dishwashers with that of engine driven lawnmowers. It has also been found that the A-weighted sound level is an indicator of the annoyance capability of commonly encountered environmental noise, such as traffic noise. Because of this, as well as its simplicity, many noise codes and community noise ordinances specify allowable A-weighted sound levels. For example: "The sound level at the property line between a manufacturing or industrial plant and a residential community must not exceed 65 dB(A) during daytime or 55 dB(A) during nighttime." Of course, other sound levels, including octave band levels and other details may be included in a more complete noise ordinance. Sound levels taken on the A-, B-, and C-weighted networks have usually been designated by dB(A), dB(B), and dB(C), respectively. The parentheses are sometimes omitted, as in dBA. The weighting networks, in effect, discard some of the sound, so it is conventional not to refer to their values as sound pressure levels, but only as sound levels - as in "an A-weighted sound level of 76 dB(A)."

Repeated exposure to high levels of mid and high-frequency sound has also been shown to cause loss of hearing, so the A-weighted sound level is also used as a means of monitoring noise in industrial facilities to evaluate the risk of noise induced hearing loss.

It is very important, when reading or reporting sound levels, to identify positively the weighting network used, as the sound levels can be quite different depending on the frequency content of the noise measured. In some cases if no weighting is specified, A-weighting will be assumed. This is very poor practice and should be discouraged.

F. CALCULATION OF A-WEIGHTED SOUND LEVEL

For analytical or diagnostic purposes, octave band measurements of a noise are much more useful than weighted sound levels. While, it is possible to calculate, with a reasonable degree of accuracy, an A-weighted sound level from octave band levels it is not possible to determine the octave band frequency content of a sound from only the weighted sound levels.

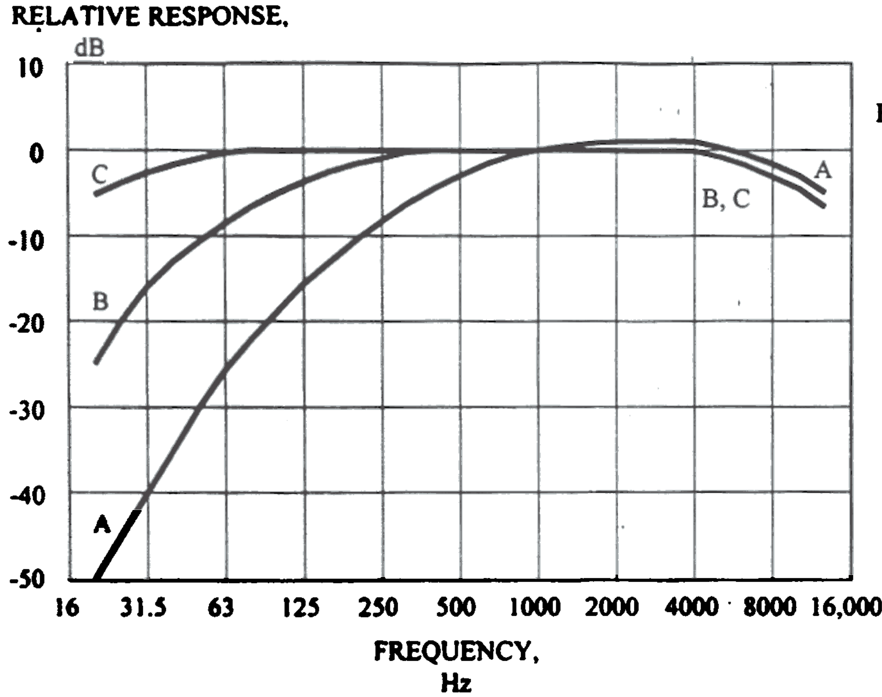
In some instances it is considered advantageous to measure or report A-weighted octave band levels. When this is done the octave band levels should not be presented as "sound levels in dB(A)," but must be labeled as "octave band sound levels with A-weighting," otherwise confusion will result. Section 1-10 contains an example of the calculation of an A-weighted sound level from octave band sound pressure levels.

1-7. SPEED OF SOUND AND WAVE-LENGTH

The speed of sound in air is given by the following:

$$c = 49.03(460 + t_F)^{\frac{1}{2}} \qquad (1\text{-}10)$$

where c is the speed of sound in air in ft./sec, and t_F is the temperature in degrees Fahrenheit.



OCTAVE FREQUENCY BAND, Hz	A-WEIGHTED FILTER RESPONSE, dB
31.5	-39
63	-26
125	-16
250	-9
500	-3
1000	0
2000	+1
4000	+1
8000	-1

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Figure 1-1. Approximate electrical frequency response of the A-, B-, and C-weighted networks of sound level meters.

A. TEMPERATURE EFFECT

For most normal conditions, the speed of sound in air can be taken as approximately 1120 ft/sec. For an elevated temperature of about 1000° F, as in the hot exhaust of a gas turbine engine, the speed of sound will be approximately 1870 ft/sec. This higher speed becomes significant for engine, and turbine exhaust muffler designs, and for some fan installations as will be noted in the following paragraph.

B. WAVELENGTH

The wavelength of sound in air is given by:

$$\lambda = \frac{c}{f} \quad (1\text{-}11)$$

where λ is the wavelength in ft, c is the speed of sound in air in ft/sec, and f is the frequency of the sound in Hz.

Over the frequency range of 50 Hz to 12,000 Hz the wavelength of sound in air at normal temperature ranges from 22 ft to 1.1 inches, a relatively large spread. The significance of this spread is that many acoustical materials perform well when their dimensions are comparable to or larger than the wavelength of sound. Thus, a 1.0 inch thickness of acoustical ceiling tile applied directly to the ceiling is quite effective in absorbing high frequency sound, but is of little value in absorbing low frequency sound.

At room temperature, a 10 ft long dissipative muffler is about 9 wavelengths long for sound at 1000 Hz and will generally be more effective than at 50 Hz where the muffler is only about 0.4 wavelengths long. At an elevated exhaust temperature of 1000°F, the wavelength of sound is about 2/3rds greater than at room temperature, so the length of a muffler of the same design should be about 2/3rds longer in order to be as effective as one at room temperature.

In the design of noise control treatments and the selection of noise control materials, the acoustical performance will frequently be found to relate to the dimensions of the treatment compared to the wavelengths of sound. This is the basic reason why it is generally easier and less expensive to achieve high-frequency noise control (short wavelengths) and more difficult and expensive to achieve low-frequency noise control (long wavelengths).

1-8. TEMPORAL VARIATIONS

Both the acoustical level and spectral content can vary with respect to time. This can be accounted for in several ways. Sounds with short term variations can be measured using the meter averaging characteristics of the standard sound level meter as defined by ANSI S1.4 [3]. Typically two meter averaging characteristics are provided, these are termed "Slow" with a time constant of approximately 1 second and "Fast" with a time constant of approximately 1/8 second. The slow response is useful in estimating the average value of most mechanical equipment noise. The fast response is useful in evaluating the maximum level of sounds which vary widely.

Longer term variations can be characterized by use of statistical methods. One such method is the "equivalent" sound level, often abbreviated L_{eq}. The equivalent sound level is a single level that is equivalent to the energy of the varying level over a specified period of time. It is in essence the time-energy average of the varying levels. Typically the equivalent level is obtained with a frequency weighting, such as the A-weighting. A second method of characterizing level variations is with the use of "exceedance" levels. These are levels that are exceeded for a specified percentage of the measurement time. For example a 10% exceedance level of 65 dB means that for 10% of the measurement time the level was 65 dB or greater. Exceedance levels are often abbreviated by $L_{\%}$, where the percent is specified. In the above example the L_{10} = 65 dB. The use of exceedance levels with frequency weighting or band filtering can provide an indication of distribution of the sound levels with respect to both time and frequency. One of the most used exceedance levels is the L_{90} level or the level exceeded for 90 percent of the measurement period. Quite often this is the quantitative measure used to qualify the "residual," "ambient," or "background" level. When presenting an exceedance level, the frequency weighting or band filtering should also be specified.

Leq

1-9. LOUDNESS

The ear has a wide dynamic range. At the low end of the range, one can hear very faint sounds of about 0 to 10 dB sound pressure level. At the upper end of the range, one can hear with clarity and discrimination loud sounds of 100 dB sound pressure level, whose actual sound pressures are 100,000 times greater than those of the faintest sounds. People may hear even louder sounds, but in the interest of hearing conservation, exposure to very loud sounds for significant periods of time should be avoided. It is largely because of this very wide dynamic range that the logarithmic decibel system is useful; it permits compression of large spreads in sound power and pressure into a more practical and manageable numerical system. For example, a commercial jet airliner produces 100,000,000,000 (= 10^{11}) times the sound power of a cricket. In the decibel system, the sound power of the jet is 110 dB greater than that of the cricket ($110 = 10 \log 10^{11}$). Humans judge subjective loudness on a still more compressed scale.

Table 1-2. Relationship between changes in sound level, acoustic energy loss, and approximate relative loudness of a sound.

Sound Level Change	Acoustic Energy Loss	Relative Loudness
0 dB	0	Reference
-3 dB	50%	Perceptible Change
-6 dB	75%	Noticeable Change
-10 dB	90%	Half as Loud
-20 dB	99%	1/4 as Loud
-30 dB	99.9%	1/8 as Loud
-40 dB	99.99%	1/16 as Loud

A. LOUDNESS JUDGMENTS

Under controlled listening tests, humans judge that a 10 dB change in sound pressure levels in the mid- and high frequency ranges represents approximately a halving or a doubling of the loudness of a sound. Yet a 10-dB reduction in a sound source means that 90 percent of the radiated sound energy has been eliminated. Table 1-2 shows the approximate relationship between sound level changes, the resulting loss in acoustic power, and the judgment of relative loudness of the changes. Toward the bottom of the table, it becomes clear that tremendous portions of the sound power must be eliminated to achieve impressive amounts of noise reduction in terms of perceived loudness.

B. SONES AND PHONS

Sones and phons are units used in calculating the relative loudness of sounds. Sones are calculated from nomograms that interrelate sound pressure levels and frequency, and phons are the summation of the sones by a special addition procedure. The results are used in judging the relative loudness of sounds, as in "a 50-phon motorcycle would be judged louder than a 40-phon motorcycle." When the values are reduced to phon ratings, the frequency characteristics and the sound pressure level data have become detached, and the noise control analyst or engineer has no concrete data for designing noise control treatments. Sones and phons are not used in this manual, and their use for noise control purposes is of little value. When offered data in sones and phons, the noise control engineer should request the original octave band sound pressure level data, from which the sones and phons were calculated. Textbooks on acoustics can give details of the calculation of sones and phons.

1-10. DECIBEL MANIPULATION

A. DECIBEL ADDITION

Decibel levels often have to be added or subtracted. However, decibels are logarithmic quantities and do not follow normal algebraic rules. Instead, decibels are first converted to energy equivalents, the energy equivalents are added algebraically, and then the total energy equivalent is converted to its decibel value. The steps in this procedure are illustrated in the example given below, of one of the more commonly used decibel manipulations, decibel addition.

The decibel sum L_s of several sound levels L_1, L_2, L_3, etc. can be obtained from the following equation:

$$L_s = 10\log\left(10^{\frac{L_1}{10}} + 10^{\frac{L_2}{10}} + 10^{\frac{L_3}{10}} + \dots\right) \quad (1\text{-}12)$$

Example:

Let $L_1 = 90$dB, $L_2 = 92$ dB, $L_3 = 94$ dB, $L_4 = 103$ dB, and $L_5 = 85$ dB. Then,

$$\begin{aligned} L_s &= 10\log(10^{9.0} + 10^{9.2} + 10^{9.4} + 10^{10.3} + 10^{8.5}) \\ &= 10\log(1\times10^9 + 1.58\times10^9 + 2.51\times10^9 + \\ &\qquad 19.95\times10^9 + 0.32\times10^9) \\ &= 10\log(25.36\times10^9) \\ &= 10\log(2.536\times10^{10}) \\ &= 4.04 + 100 \\ &= 104\text{ dB} \end{aligned}$$

B. DECIBEL SUBTRACTION

Often it is necessary to estimate the noise level of a specific source located in the midst of other noise sources, without having the opportunity of turning off the other nearby noise sources. In this situation one approach is to measure the noise at one location with the specific source both on and off, with all other sources operating. Then, at each measured location, let:

L_s = the total sound level, in dB, of the desired machine (when ON) plus all the other "background" noise of the other equipment (this is <u>measured</u>);
L_2 = all the other "background" noise, when the desired machine is OFF (this is <u>measured</u>);
L_1 = the sound level, in dB, of the desired machine, in the absence of the other "background" noise (this is <u>estimated</u>, not measured).

Using Table 1-3, convert the dB values to energy equivalents; subtract L_2 (energy equivalent) from L_S (energy equivalent) to get L_1 (energy equivalent); then convert L_1 (energy equivalent) back to L_1 (dB value).
Example:

Let $L_s = 96$ dB, $L_2 = 92.5$ dB. Determine L_1.

<u>Level</u>	<u>Decibel Values</u>	<u>Energy Equivalents</u>
L_s	96 = 6 + 90	3.98×10^9
$-L_2$	$-92.5 = 2.5 + 90$	<u>-1.78×10^9</u>
	(subtracting)....	2.20×10^9
	(converting back to decibels)....	3.5 + 90 dB
	$L_s - L_2 = L_1$	= 93.5 dB

This procedure would be followed for each octave frequency band of noise and for each measurement location. The accuracy of the estimate is limited by the accuracy of the measured data.

Table 1-3. Conversion between decibel values and energy equivalents, for use in "decibel addition."

Part A: Conversion Table

Units of Decibels	Energy-Equivalent Units	Tens of Decibels	Energy-Equivalent Units
0	1.00	0	$10^0 = 1$
0.5	1.12	10	$10^1 = 10$
1.0	1.26	20	$10^2 = 100$
1.5	1.41	30	$10^3 = 1000$
2.0	1.58	40	10^4
2.5	1.78	50	10^5
3.0	2.00	60	10^6
3.5	2.24	70	10^7
4.0	2.51	80	10^8
4.5	2.82	90	10^9
5.0	3.16	100	10^{10}
5.5	3.55	110	10^{11}
6.0	3.98	120	10^{12}
6.5	4.47	130	10^{13}
7.0	5.01	140	10^{14}
7.5	5.62		
8.0	6.31		
8.5	7.08		
9.0	7.94		
9.5	8.91		
10.0	10.00		

Part B: Procedure for use of Conversion Table

1. Separate decibel value into "units" and "tens" values, as in

   85 dB = 5 dB + 80 dB

2. Determine energy equivalents from table for the separated decibel values; then multiply those energy equivalents, as

$$\begin{array}{ccc} 5\text{ dB} & + & 80\text{ dB} \\ \downarrow & \downarrow & \downarrow \\ 3.16 & \times & 10^8 \end{array} \quad \text{energy units}$$

3. For adding decibels, convert all decibel levels to energy units. Add the energy units, as in

$$\begin{array}{lcl} 85\text{ dB} & = & 3.16 \times 10^8 \\ 81\text{ dB} & = & 1.26 \times 10^8 \\ 76\text{ dB} & = & 3.98 \times 10^7 = 0.40 \times 10^8 \\ \text{Adding:} & & 4.82 \times 10^8 \end{array}$$

4. Convert energy units back to decibels, using the table in reverse order, as in

$$\begin{array}{ccccc} 4.82 & \times & 10^8 & & \\ \downarrow & \downarrow & \downarrow & & \\ 7\text{ dB} & + & 80\text{ dB} & = & 87\text{ dB} \end{array}$$

C. SHORT METHODS FOR DECIBEL ADDITION

There are a number of simplifying methods for the addition of decibel values, and two methods are presented. A very simple, but usually adequate, schedule for obtaining the sum of two decibel values :

Schedule A For adding any two decibel levels to an accuracy of about 1 dB:

When Two Decibel Values Differ By:	Add the Following Number to the Higher Value:
0 or 1 dB	3 dB
2 or 3 dB	2 dB
4 to 9 dB	1 dB
10 dB or more	0 dB

When the above schedule is used, the final sum will usually be correct to within 1 dB. From this schedule, for example, it is found that:

90 dB + 92 dB = 94 dB
75 dB + 81 dB = 82 dB
60 dB + 70 dB = 70 dB.

To add a number of equal-valued levels the following schedule may be used.

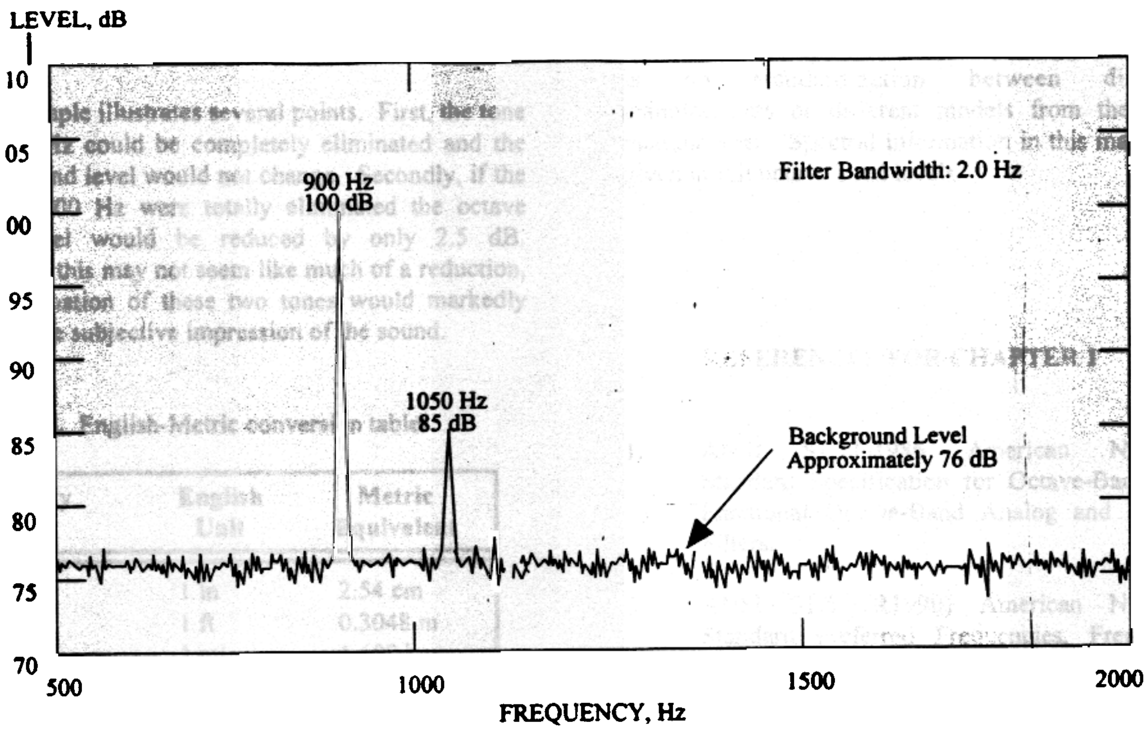

Figure 1.2. Example of narrow band spectrum plot.

A-weighted levels can always be calculated from octave band data, but octave band data cannot be determined accurately from the A-weighted level.

Another example of the use of decibel addition related to the previous discussion of bandwidth analysis is the determination of the band level when the spectrum consists of both broad band noise and one or more tonal components. If dominant tones are present within the band, then the level of the tones have to be considered separately from the broadband energy within the band. This is demonstrated with an illustration. Assume a measured spectrum level as shown on Figure 1-2. This is a spectrum obtained with a 2 Hz wide filter. This spectrum is flat with the exception of a tone at 900 and 1,050 Hz. In order to obtain the level that would have been measured with an octave band filter centered at 1,000 Hz we would make the following calculations.

First the broadband portion, with a level of approximately 76 dB, is adjusted for the change in bandwidth as given in equation 1-9 above. The bandwidth of the 1,000 Hz octave band is 707 Hz (1414 - 707). Therefore the broadband level is determined as follows:

$$76 + 10\log(707/2) = 76 + 25.5 = 101.5 \text{ dB}$$

Secondly the tonal level of 100 at 900 Hz, and 85 dB at 1050 Hz is added to the broadband level by decibel addition. Therefore the expected octave band level at 1,000 Hz is determined as follows:

$$101.5 \text{ dB} + 100 \text{ dB} + 85 \text{ dB} = 104 \text{ dB}$$

In practice the broadband portion of the signal is not always as flat as that shown on Figure 1-2, in which case some judgment has to be made as to the average energy level within the octave band, or, the octave band has to be further subdivided, the results computed for each subdivision and then recombined with decibel addition. In addition, tones are not always as concentrated, with respect to frequency, as that shown on the figure. In which case some

5. What is the wavelength of a 100-Hz sound signal in air at 62°F? What is the wavelength of a 2000-Hz sound at 62°F?

6. Add the following four decibel levels by each of the decibel addition procedures offered in the manual: 75, 82, 87, and 84 dB.

7. A small shop air compressor has the following sound pressure levels in 8 of the 9 octave bands:

Hz	63	125	250	500	1k	2k	4k	8k
dB	88	87	86	89	88	83	79	75

What are the overall and A-weighted sound levels for these octave band values?